Estimating Regional Contributions to Atmospheric Haze Using GIS

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ABSTRACT

ArcObjects was used to develop a customized spatial mapping tool to aid in characterizing relationships between air pollutant emissions and downwind air quality observations. The tool, called Emission Impact Potential (EIP), combines backward-trajectory meteorological analyses with emission inventory data to calculate and visualize emissions source regions most likely to impact a specified air pollution monitoring site. EIP generates spatial probability distributions that account for the spatial distribution of emissions and wind trajectory probability distributions. Thus, pollutant emissions that are most likely to affect a measurement location are weighted more heavily in correlation analyses. This analysis approach helps to identify emissions source regions likely to impact specified monitoring sites and to more intelligently target emission reductions to improve downwind air quality.

INTRODUCTION

The Central States Regional Air Planning Association (CENRAP) is responding to the U.S. Environmental Protection Agency's (EPA's) mandate to protect visibility in Class I areas by researching visibility-related issues and developing a regional haze plan for the CENRAP region, which includes Texas, Oklahoma, Louisiana, Arkansas, Kansas, Missouri, Nebraska, Iowa, and Minnesota. In order to produce an effective regional haze plan, the CENRAP must develop a conceptual model of the phenomena that lead to episodes of low and high visibility in the states in the CENRAP region. CENRAP needs information that can be used for planning photochemical modeling assessments, including selection of episodes, geographic areas, and effective control strategies to be modeled.

Backward-trajectory analyses have been applied in various air quality studies to examine potential sources of measured pollutants at a receptor site.[1-5] Source regions identified by backward-trajectory techniques can be compared to emissions data maps to verify that the pollutants (or their precursors) measured at the receptor site are emitted in those regions. Photochemical modeling can be employed to fully explore the relationship among emissions, atmospheric dynamics, and measured concentrations. However, modeling is expensive and time consuming; therefore, it is typically applied to selected case studies. As a preliminary screening analysis, we employed a simple method to mathematically combine emission inventory data with a backward-trajectory ensemble technique. This technique, called emission impact potential (EIP), shows the possibility of individual source areas that may contribute to downwind pollution based on emission inventories and air mass trajectories alone.

METHODS

Emission Inventory

Emission inventory data for 2002 were acquired for the United States, Canada, northern Mexico, and the Gulf of Mexico from the regional planning organizations and other sources. Information about the criteria pollutants (NO_x, SO_2, PM_{10}, $PM_{2.5}$, NH_3, CO, and volatile organic compounds [VOCs]) was collected into a single North American emission inventory in a SQL Server database. The inventory was resolved on a county level for the United States, on a regional municipality level for Canada, on a municipio level for Mexico, and on a one-degree grid for the Gulf of Mexico. For Canada, emissions information was only available at the province level. These emissions were allocated to the municipality level using population density. Figure 1 is a map of NO_x emission density from the developed inventory.

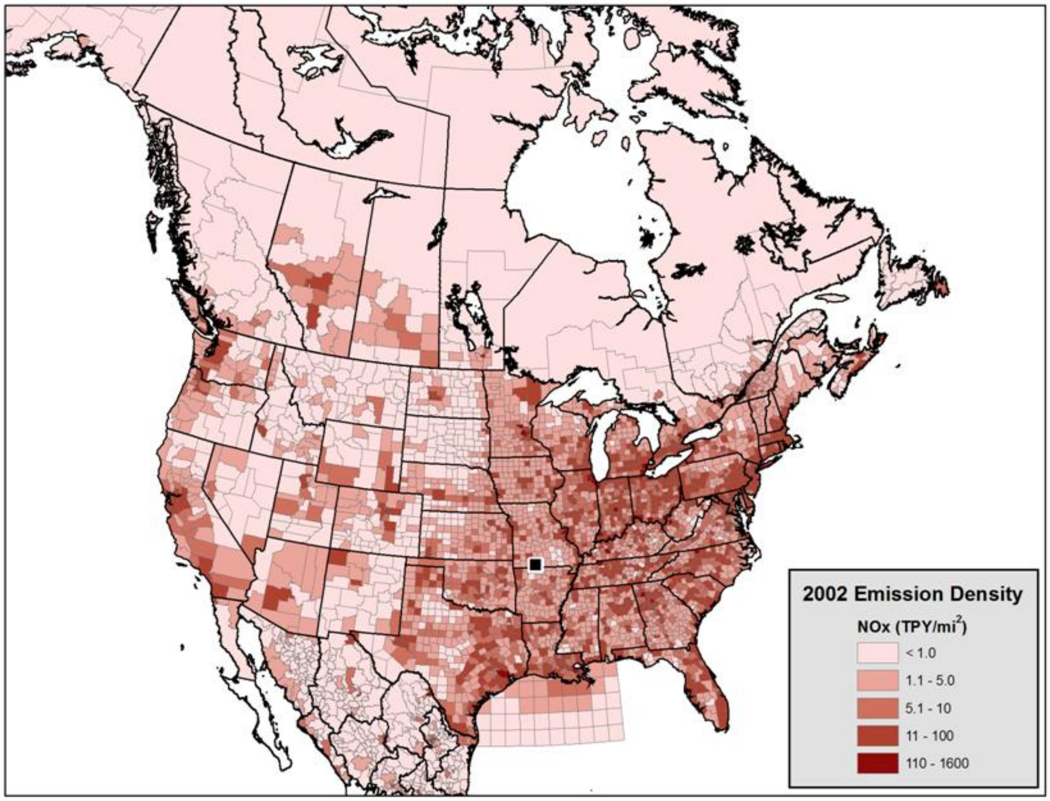

Figure 1. 2002 North American emission inventory NO_x emission density.

Spatial Probability Density

The National Oceanic and Atmospheric Administration (NOAA) HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model[6] was used to determine transport patterns to the receptor site. An ensemble of backward-trajectory model runs was performed to represent the various possible wind patterns on each day of interest. For visibility protected (Class I) areas, such as Hercules Glades Wilderness, days with the 20%-worst and the 20%-best visibility are of most interest. Data from the Interagency Monitoring of Protected Visual Environments (IMPROVE) network for every third day from March 2001 through 2003 were used to determine the dates of best and worst visibility. The parameters used to run the trajectories are shown in Table 1. The trajectories were limited to 72-hr endpoints to minimize model uncertainties.

Table 1. Parameters used to run the NOAA HYSPLIT model.

Parameter	Value
Starting heights	50, 300, 700 m
Run time	72 hours
Minimum valid data points	75%
Starting hours	0, 4, 8, 12, 16, 20
Top of model	10,000 m
Model data	EDAS
Vertical motion	Isobaric

The hourly points from all trajectories over all days of interest are combined using the Spatial Probability Density (D_0), which is a kernel density of all hourly trajectory points, normalized to a maximum value of one:

$$D_0 = \frac{D_c}{\hat{D}} \qquad \textbf{(1)}$$

where

D_c = Density at grid cell c

$\hat{D}$ = Maximum density over all grid cells (density at receptor site)

$$D_c = \sum_{i=1}^{n} \kappa_R(r_n) \qquad \textbf{(2)}$$

where r_n = distance between grid cell center and hourly trajectory point n

R = search radius

$$\kappa_R(r) = \text{kernal density function} = \begin{cases} \dfrac{3}{\pi R^2}\left[1-\left(\dfrac{r}{R}\right)^2\right] & for\ r < R \\ 0 & for\ r \geq R \end{cases}$$

The search radius *R* was determined dynamically by dividing the geographic extent of all hourly trajectory points by 30.[7,8] Figure 2 shows the spatial probability density map for poor visibility days at Hercules Glades Wilderness. A value of one indicates that all trajectories pass near a grid cell, while a value closer to zero denotes an area over which very few trajectories pass. Density was calculated using the raster tools available in the ArcGIS Spatial Analyst extension.

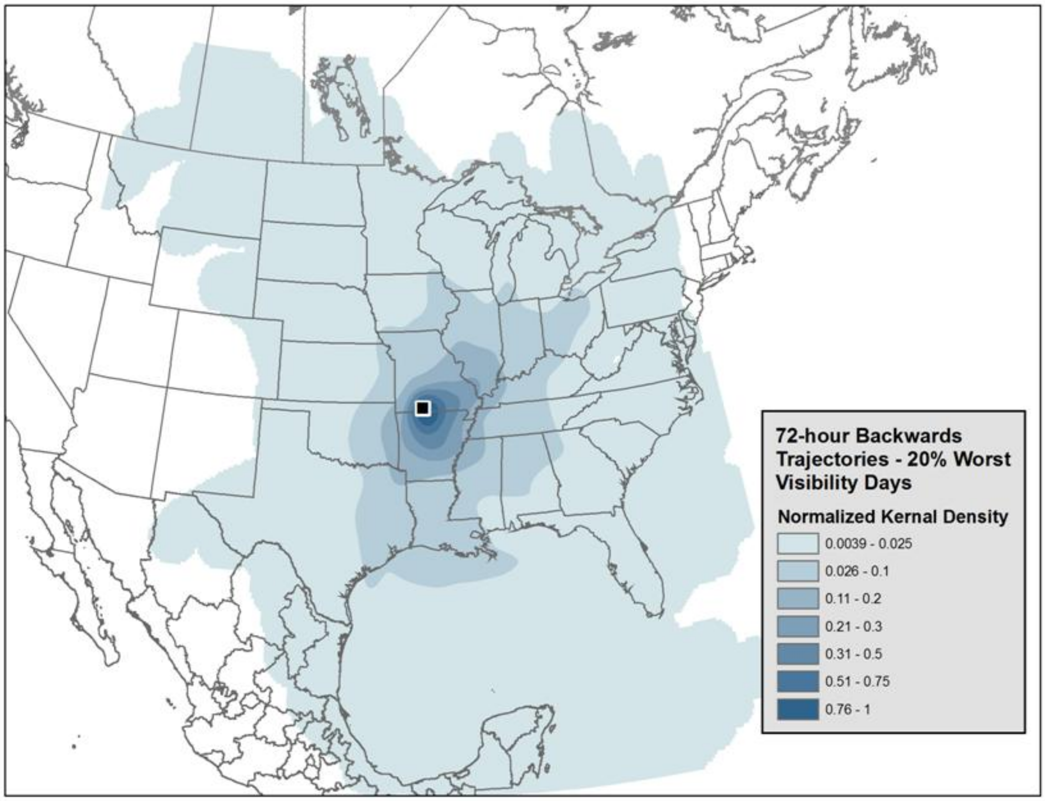

Figure 2. Spatial Probability Density for Hercules Glades Wilderness on the 20% worst visibility days.

Emission Impact Potential (EIP)

The Spatial Probability Density is used to weight the emissions from individual counties, providing an estimate of a county's potential to impact the receptor. The EIP of any county is calculated as:

$$EIP = \frac{E_p * D_0}{f\,(\text{distance})} \tag{3}$$

where

E_p = county total emissions of pollutant p

D_0 = spatial probability density at the county centroid

f = function of distance between county and receptor

The EIP may be divided by a distance function to roughly account for dilution and increased uncertainty in model outputs far from the receptor site. However, for this study, $f = 1$.

Automation

The EIP process was built within ArcGIS using Visual Basic for Applications (VBA) and ArcObjects. EIP is one of a suite of GIS tools developed for determining the probability of regional source contributions to haze (PORSCH). The tools make heavy use of the automation functionality provided by ArcObjects.

Trajectory endpoints are converted to a density surface using the raster tools available in the Spatial Analyst extension. Input data are stored in a Microsoft SQL Server database and are accessed programmatically using Microsoft ActiveX Data Objects.

RESULTS

Nitrogen Oxides (NO_x)

The NO_x emission density by county (or the equivalents for Canada, Mexico, and the Gulf of Mexico) is shown in Figure 3. Counties with high NO_x emission density generally contain major cities or large point sources. Hercules Glades Wilderness is shown as a black square in southern Missouri.

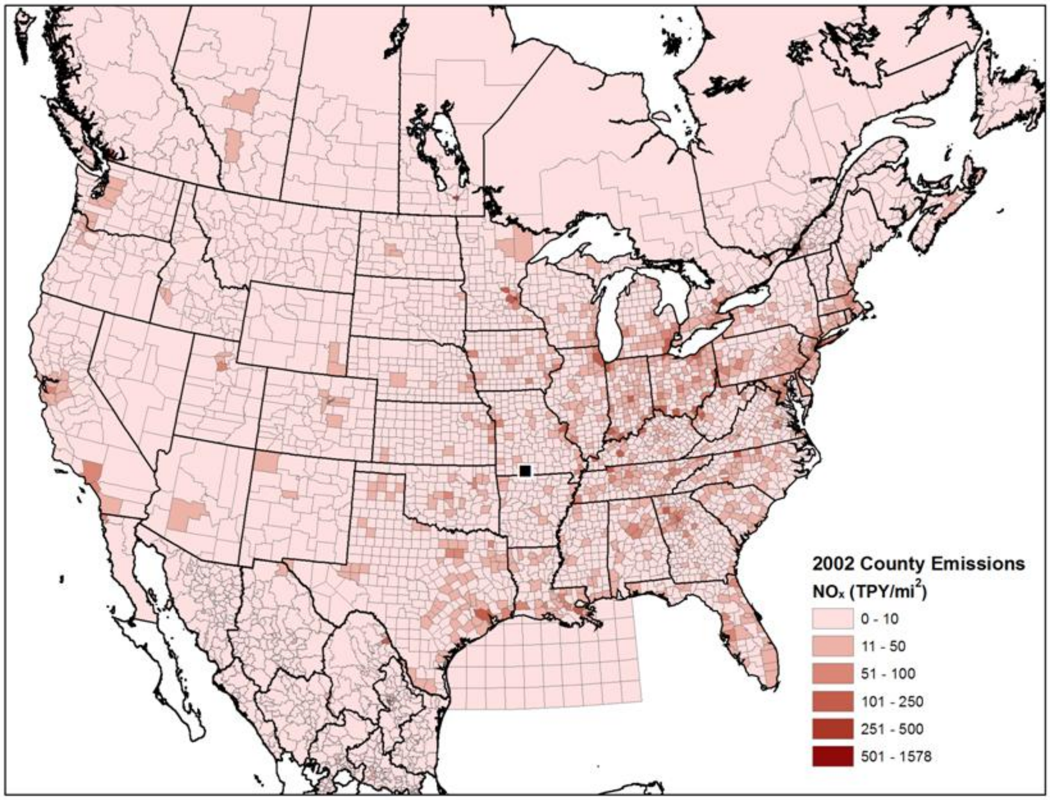

Figure 3. NO_x emission density by county or equivalent.

Figure 4 shows the NO_x EIP values by county for the 20%-worst and 20%-best visibility days. When visibility at Hercules Glades is poor, trajectories are predominantly from the south and east, passing over areas of high NO_x emission, such as Texas, Louisiana, and the Ohio River Valley. On days with the best visibility, much of the airmass impacting Hercules Glades originates from the northwest, though winds from the south remain important. Figure 5 shows the fraction of total EIP for the best and worst visibility days on the same map, highlighting the spatial differences between the county-level NO_x EIP. On the best visibility days, several counties along the Missouri River contribute the most to EIP. The emissions impact from these counties is less important on the worst visibility days. Overall, the EIP density (EIP divided by county area) is 7% higher on the worst visibility days than on the best days.

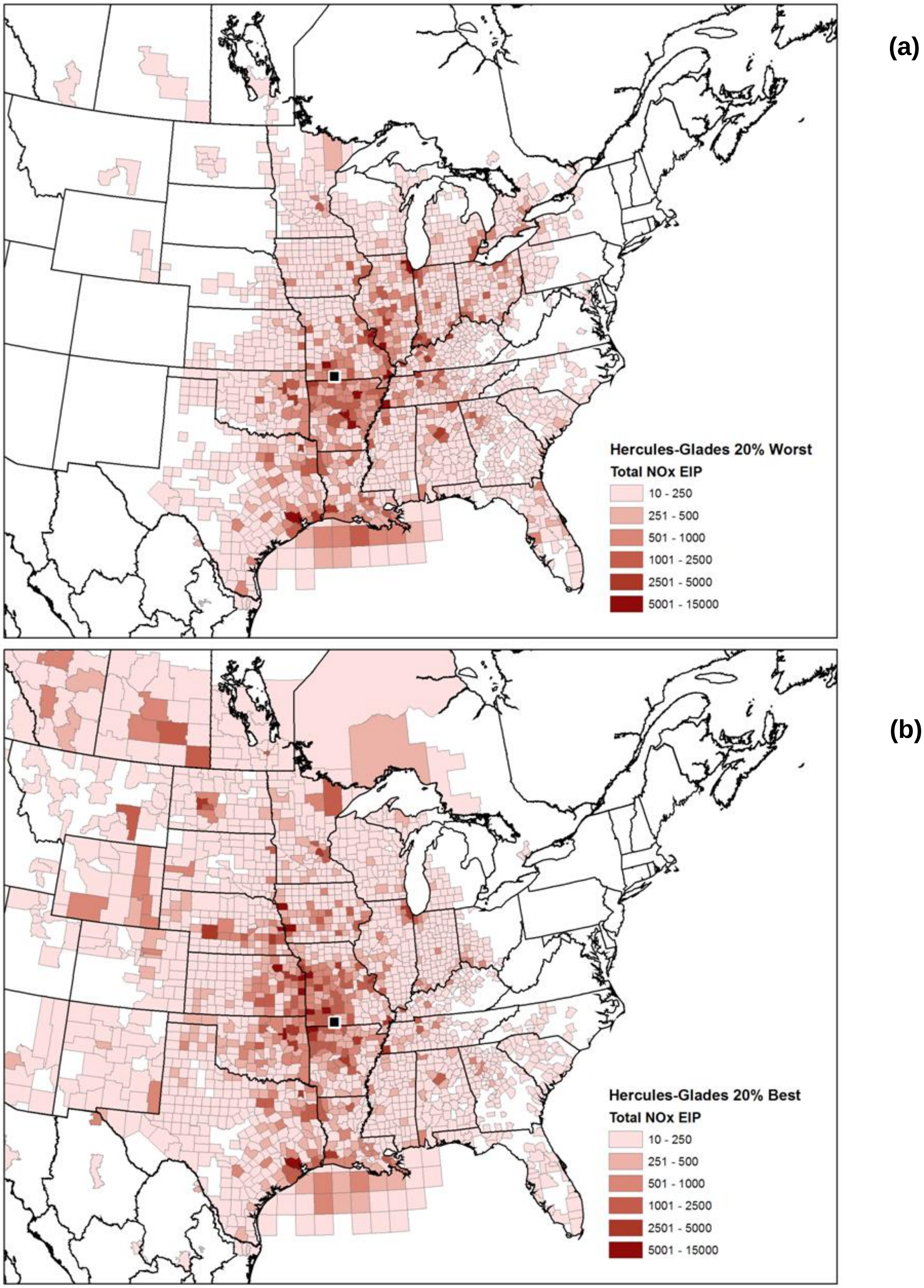

Figure 4. NO_x EIP for the (a) 20%-worst days and (b) 20%-best days.

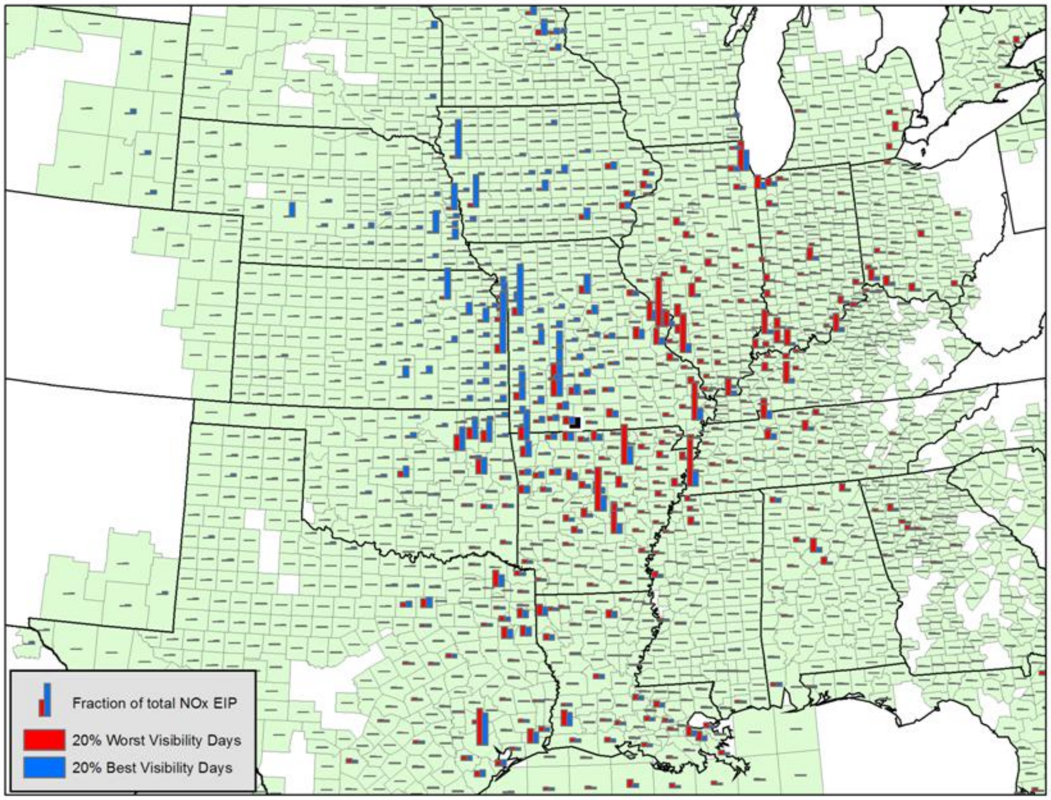

Figure 5. Fraction of total NO_x EIP by county on the best and worst visibility days.

The emission inventory can also be queried by pollutant source types. Figure 6 shows the contribution to EIP aggregated to the state level, broken down by major source type (source classification code tier 1). The spatial pattern at the state level is similar to that at the county level. For the 20%-worst visibility days, 52% of total NO_x EIP comes from the CENRAP domain, compared to 76% on the 20%-best visibility days. Though the NO_x EIP on the best and worst visibility days varies spatially, the contributing source categories are nearly identical, with mobile sources making up about 50% of total EIP, and the remainder resulting largely from point and area combustion sources. Table 2 lists the major contributing sources of NO_x EIP at Hercules Glades.

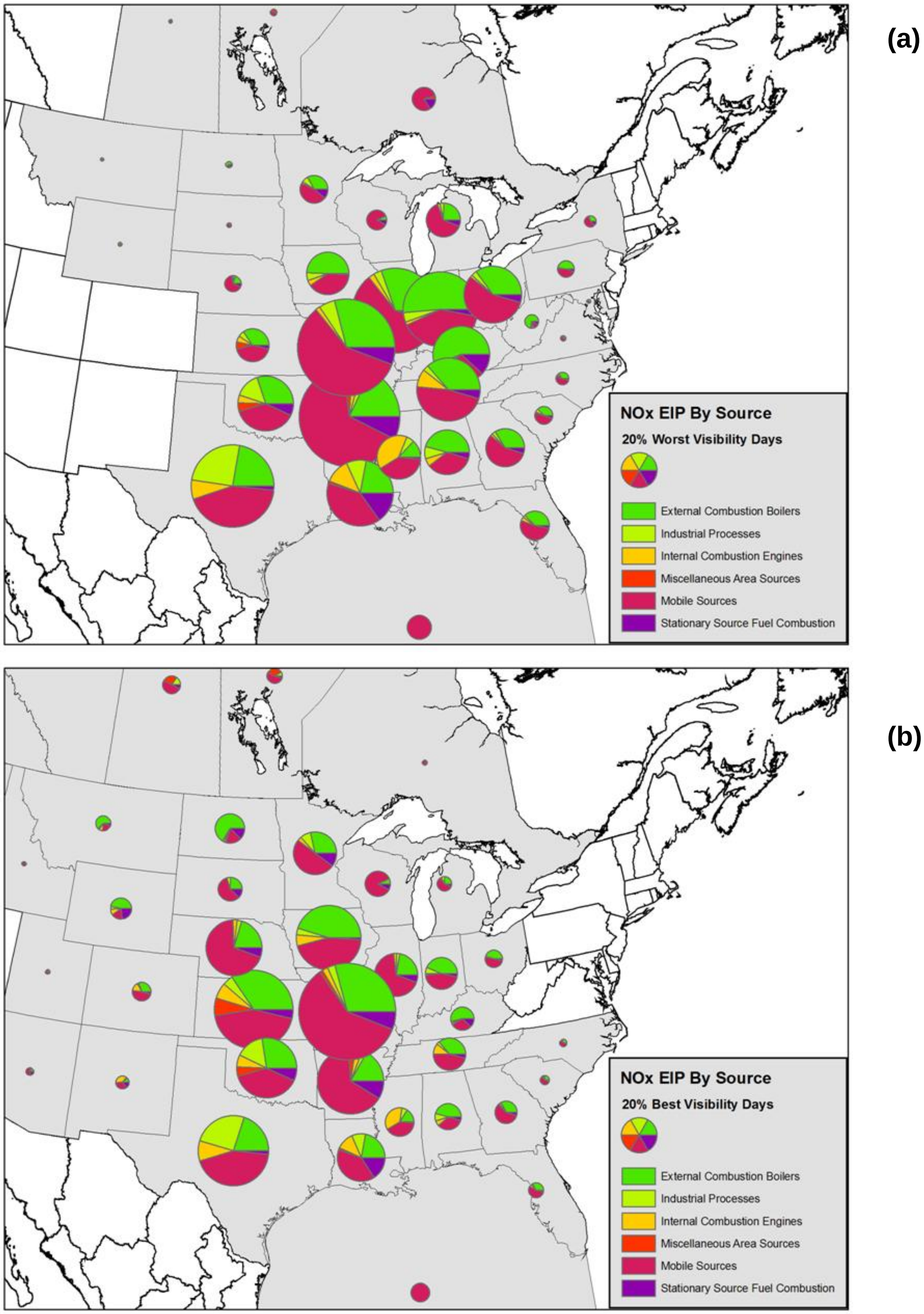

Figure 6. State NO_x EIP by source category on the (a) 20%-worst days and (b) 20%-best days.

Table 2. Major sources of NO_x EIP at Hercules Glades Wilderness.

Source	NO_x EIP 20%-Worst Days (% of total)	NO_x EIP 20%-Best Days (% of total)
Electric Generation	27	25
Gasoline Highway Vehicles	17	16
Diesel Highway Vehicles	17	15
Industrial Boilers/Engines	9	11
Off-highway Diesel Vehicles	6	8
Railroad Equipment	5	7
Commercial Marine Vessels	4	2
Oil and Gas Production	2	3
Mineral Products	2	2
Other	11	11

Sulfur Dioxide (SO_2)

The SO_2 emission density by county from the North American inventory is shown in Figure 7. The highest values are generally in counties with one or more significant point sources; these point sources dominate the SO_2 emission inventory.

Figure 8 shows the SO_2 EIP for the 20%-worst and 20%-best visibility days. Note that the trajectories used to calculate EIP for both NO_x and SO_2 are identical; therefore, any differences in EIP between the two are due solely to differences in the emission inventory. For the 20%-worst days, high EIP values come from the south and east. For the 20%-best days, high EIP values mostly come from the north and west.

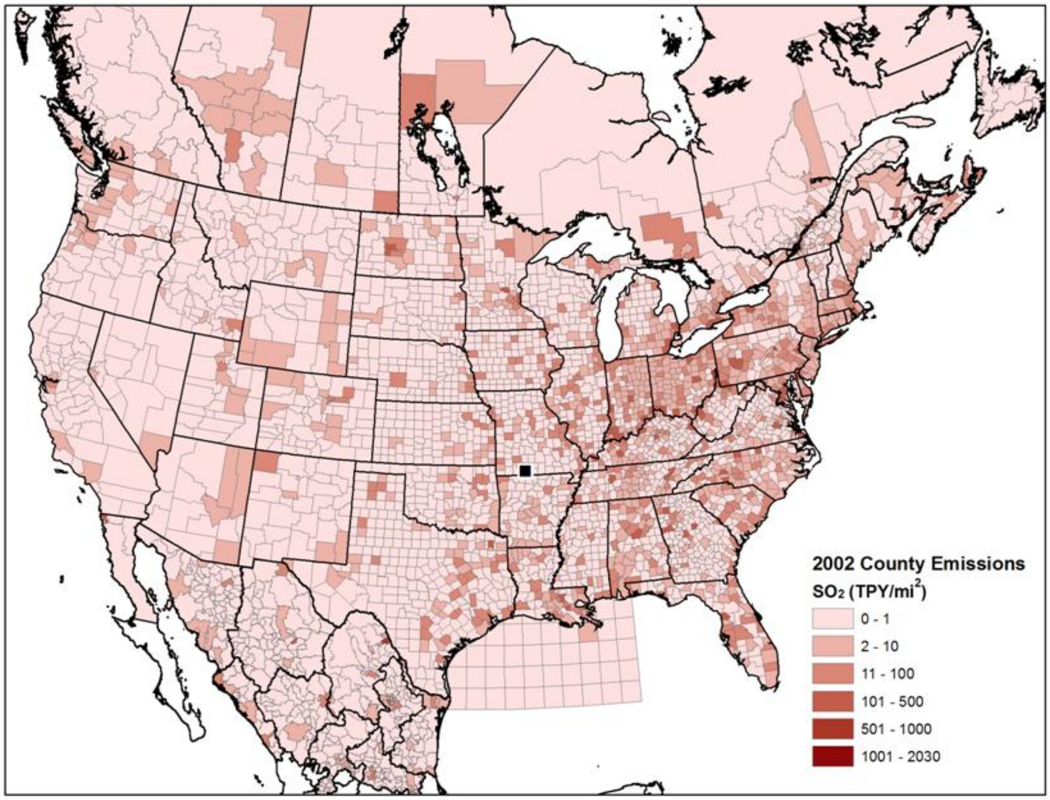

Figure 7. SO_2 emission density by county.

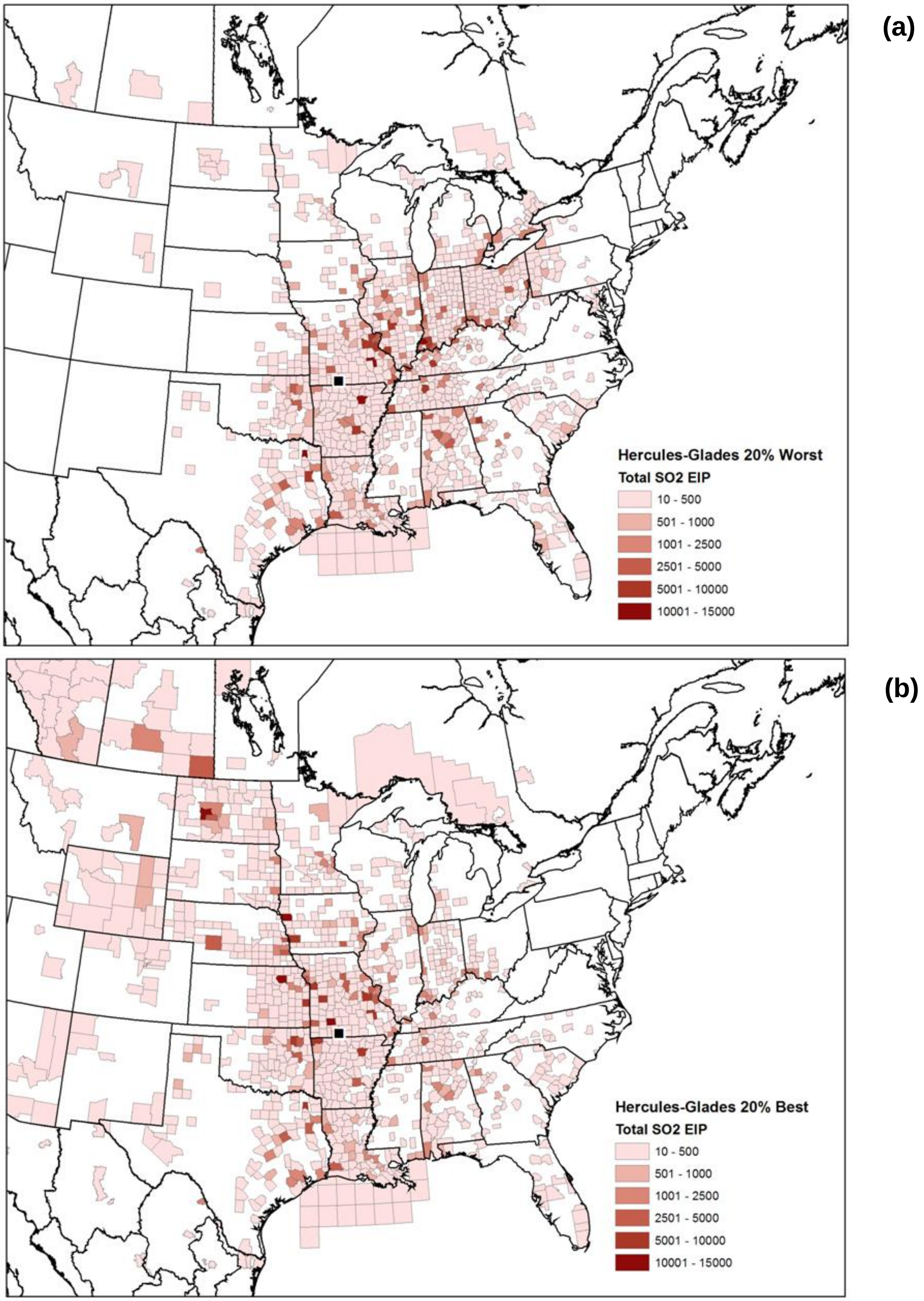

Figure 8. SO_2 EIP for the (a) 20%-worst days and (b) 20%-best days.

Figure 9 shows the spatial difference between the SO_2 EIP on the best and worst visibility days. Counties with large SO_2 emissions are located on all sides of the site; however, the EIP density for the 20%-worst days is 40% higher than the EIP density on the 20%-best visibility days, that is, the potential for SO_2 emissions to impact Hercules Glades according to this metric is consistent with observed visibility.

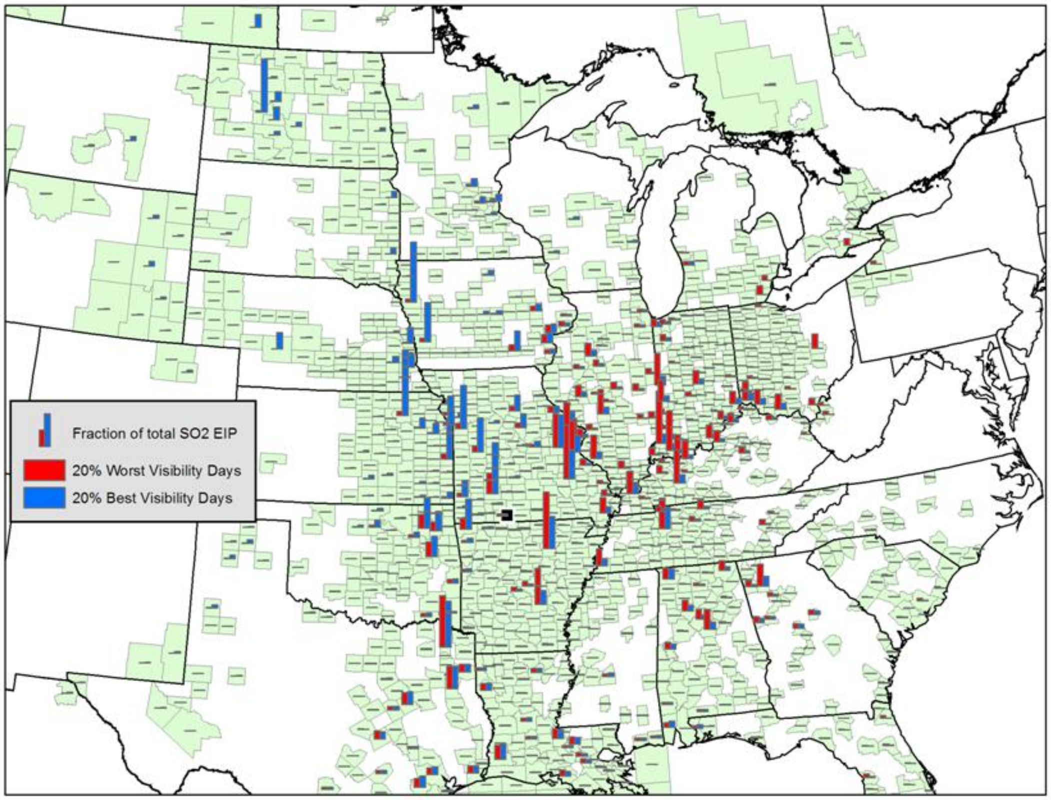

Figure 9. Fraction of total SO_2 EIP by county on the best and worst visibility days.

Aggregating the SO_2 EIP by state and showing contributions by source type reveals the dominance of point sources, particularly external combustion boilers (i.e., coal-fired power plants) as shown in Figure 10. This view also highlights contributions from within and outside the CENRAP domain. The CENRAP states comprise 42% of the EIP on the worst visibility days and 69% on the best visibility days. The greatest contributing source types to the SO_2 EIP are shown in Table 3. Note that emissions associated with electric power generation account for greater than two-thirds of the total SO_2 EIP.

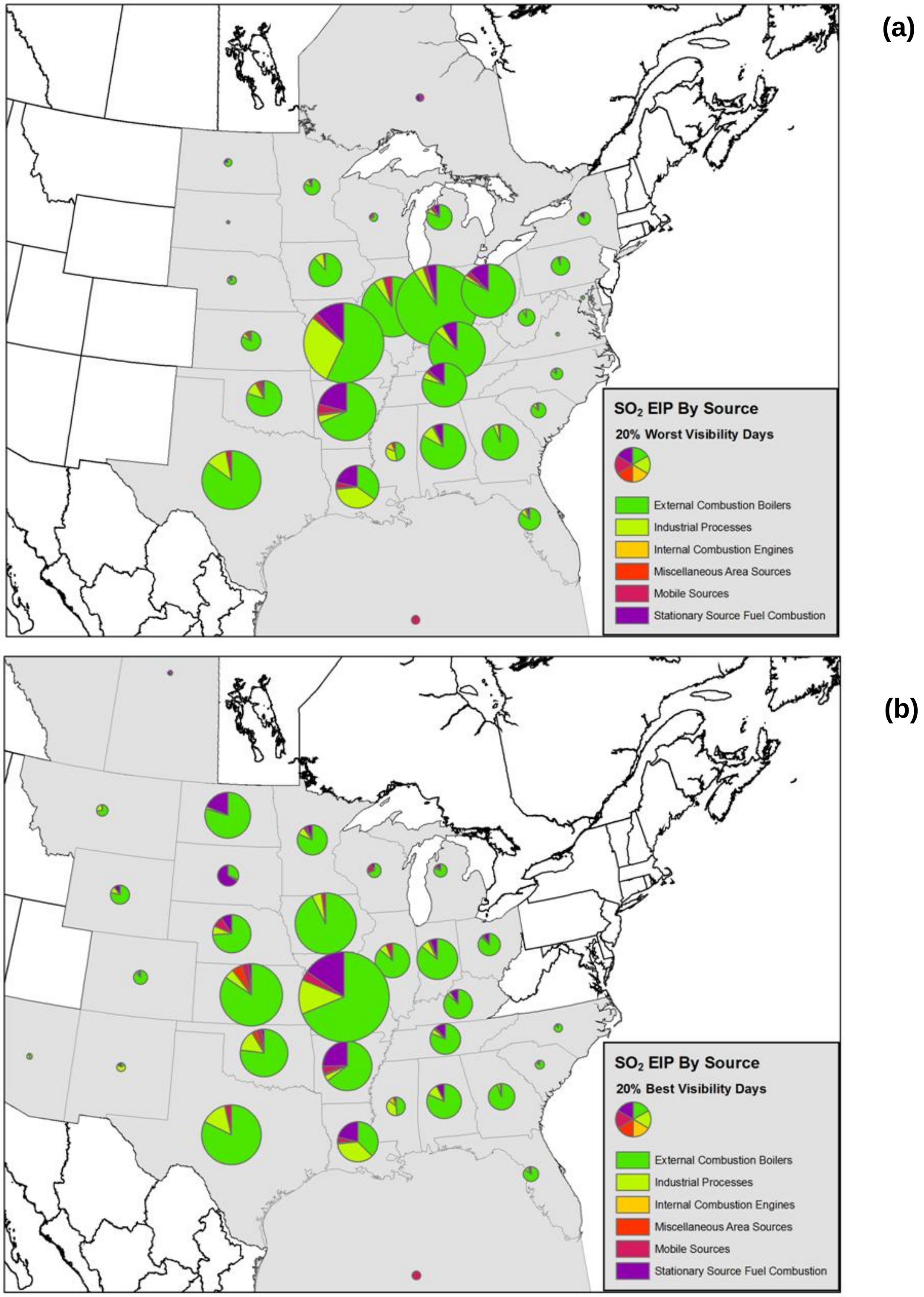

Figure 10. State SO_2 EIP by source category for the (a) 20%-worst days and (b) 20%-best days.

Table 3. Major sources of SO_2 EIP at Hercules Glades Wilderness.

Source	SO_2 EIP 20%-Worst Days (% of total)	SO_2 EIP 20%-Best Days (% of total)
Electric Power Generation	69	68
Industrial Combustion	9	15
Primary Metal Production	4	2
Mineral Products	2	2
Chemical Manufacturing	2	2
Petroleum Industry	2	2
Others	12	8

DISCUSSION

The emission inventory contained the most data for SO_2 and NO_x; therefore, they were chosen for this preliminary analysis. Hercules Glades Wilderness was chosen from several Class I sites within the CENRAP because visibility data were available for this site, and a previous analysis[9] showed that visibility at this site is driven primarily by sulfate. As inventories are completed for other pollutants such as $PM_{2.5}$, PM_{10}, NH_3, and VOCs, Sonoma Technology Inc. (STI) would like to perform similar EIP analyses for these pollutants, and for several other sites. Although relative source type contributions did not vary significantly between the best and worst visibility runs in this analysis, this may not be the case for other pollutants and/or sites. If they do vary, it would be useful to look at specific source categories for which new pollution controls could be installed.

Data for Hercules Glades Wilderness showed only a small difference between the NO_x EIP density for the 20%-worst and 20%-best visibility days, despite a substantial difference in the transport pattern. By contrast, the SO_2 EIP density was 40% higher for the 20%-worst visibility days. This analysis suggests that SO_2 EIP is a potential driver for poor visibility at the site. Because SO_2 is a precursor to sulfate, this conclusion is consistent with our understanding that sulfate is the primary cause of poor visibility at this site. Calculating EIP density on a daily basis and exploring its correlation with monitored visibility concentration would be useful.

On the 20%-best days, nearly 69% of the SO_2 EIP is within the CENRAP domain. CENRAP has the opportunity to maintain the visibility on those days by not increasing emissions in upwind counties. This opportunity is not as strong for the 20%-worst days, when only 42% of EIP originates within the CENRAP states.

Once the tools have been developed, EIP analysis is simple and quick to perform and can be useful for characterizing how emissions affect receptors. However, this tool is not intended to replace photochemical modeling. Its design omits complicating factors such as photochemistry and deposition. The numerical EIP value is a new metric, and quantitative assessments can only be made on a relative basis.

CONCLUSIONS

EIP is a simple mathematical tool for combining meteorological data with emission inventory information to determine how emissions away from a site could affect pollutant concentrations at the site. ArcObjects provided a powerful framework for the rapid development of this tool. EIP was calculated for SO_2 and NO_x for Hercules Glades Wilderness in southern Missouri. According to the analysis, the SO_2 EIP is a better predictor of visibility at this site than the NO_x EIP. Further analyses will explore other pollutants and sites.

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